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A SYNOPTIC STUDY OF THE MECHANICS OF COLD LOW FORMATION

Prepared by

Richard J. Reed

Massachusetts Institute of Technology

Cambridge, Massachusetts

H. G. Houghton, Director

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FOREWORD

The present study attempts to obtain useful information concerning the mechanics of one important type of pressure system—the cold low—through the analysis of a selected case history. Most of the tedious measurements involved were performed by Mr. L. Van der Hoven. Mr. E. Kessler also shared in the measuring program. The research reported in Section C is entirely the work of Mr. Van der Hoven.

Prof. J. M. Austin rendered valuable assistance in the selection and organization of subject matter.

A Synoptic Study of the Mechanics of Cold Low Formation

A. Introduction

A weather phenomenon of considerable importance, both to the practicing forecaster and to the theoretical meteorologist, is the so-called "cold low". From the standpoint of synoptic meteorology it is of such frequent occurrence and distinctive behavior that it may be regarded as a separate forecast problem. Theoretically it is of interest because of its role as an exchange medium in the general circulation.

As the name implies, the cold low is an atmospheric depression, or region of cyclonic circulation, within which tropospheric temperatures are cold relative to the surroundings. In accordance with the thermal wind relationship the strength of the cyclonic circulation increases with elevation reaching a maximum in the vicinity of the tropopause. Above that level the temperature gradient reverses with a corresponding decrease in wind velocity.

For descriptive purposes cold lows may be divided into three broad classes based on their position relative to the main belt of westerlies.

1. During periods of excessive meandering of the jet stream a pinching-off process frequently occurs in which an island of cyclonically rotating cold air becomes detached south of the main belt of westerlies. Such lows are often referred to as "cut-off lows". They are characterized by sluggish movement and are frequently found near the Azores and off the coast of Southern California.

cold low is well established from a large number of case studies. Fig. 1 depicts the major features for an idealised situation. The thin solid lines represent the intersection of the potential temperature surfaces with the vertical plane running east-west through the axis of the low. The raised surfaces in the troposphere show the cold tropospheric core; the sunken surfaces above, the warm core in the stratosphere. The wind field is represented by the broken lines. Highest velocities occur in a jet (J) near the tropopause. The latter (heavy solid line) is fractured in the vicinity of the jet, while a separate, oftentimes multiple, tropopause is observed at relatively low elevations in the central regions of the low.

Although sufficient knowledge is now available concerning the final structure of the cold low, information regarding the manner of its formation is still fragmentary and contradictory. Few detailed analyses of the development of the symmetrical temperature field are to be found. Still less has been written concerning the evolution of the wind or vorticity field, and studies which consider both fields simultaneously with emphasis on consistency between the dynamic and thermodynamic aspects of the development are rare.

Among the first to offer an explanation of cold low formation was V. Bjerknes (1921). He likens the action to that of a centrifugal pump. The strong circulation near the tropopause pumps tropospheric air up along the axis and sucks stratospheric air down. Adiabatic cooling and warming, respectively, account for the characteristic temperature fields. Fig. 2 patterned after a diagram of a dynamic low appearing in Scherhag (1950) shows a similar vertical circulation. On the other

hand, in discussing the Kaltlufttropfen, Scherhag attributes the cold pool to a pinching-off of cold air of polar origin.

Palmen (1950) has demonstrated the origin of the vorticity at high levels in the cold low and has presented evidence that the cold air is advected into the low from the north and becomes symmetrical with the low as a result of greater subsidence on the northern border. A circulation scheme similar to that in Fig. 2 is contained in a model by Hsieh (1949). Supposedly the jet stream exerts frictional drag on the vortex thereby producing ascending motion and cooling in the central regions.

The preceding brief historical review raises many questions regarding cold low formation. How much of the cooling is due to horizontal advection? How much to ascending motion? How do these two effects differ in importance relative to the axis of the low at various elevations? And most significantly, are the various thermal pictures consistent with the dynamics of the situation? In other words, do they explain the simultaneous formation of symmetrical temperature and vorticity fields without violating dynamic principles?

The present paper seeks an answer to these questions through the detailed study of a case history. In brief, it attempts to give a consistent dynamic and thermal picture of how a selected cold low came into being. Since it cannot be assumed that each of the three classes of cold lows discussed above have similar origins, it is important to note that the case under consideration was typical of the middle group. It formed in the main belt of westerlies, was migratory in nature and was accompanied by widespread weather activity.

In the present study special attention will be devoted to

and (3) can be seen from the fact that the change in thermal stability ($\partial\theta/\partial z$) of an individual air parcel is a measure of the vertical stretching and hence, from continuity considerations, of the horizontal divergence. Evidence for or against the presence of the divergent area in Fig. 2 can be obtained, therefore, by following back along the trajectory of the air and noting the change in $\partial\theta/\partial z$.

B. Case of March 11 - 13, 1951.

Figs. 3 to 8 show the evolution of the 500-mb contour pattern from small amplitude trough to closed low. The entire development takes place over the North American continent where aerological data are comparatively abundant. It was primarily this factor which governed the choice of the present case history. The general features of the temperature and contour fields are evident from the figures. More specific features of the development, which illustrate the dynamic and thermal processes involved, are presented in the following charts and diagrams.

a. Average Relative Winds. It has long been recognized that extratropical disturbances are wave phenomena in the sense that they do not act as solid bodies of rotation. Except in the dying stages there is a continual flow of mass into and out of the low pressure area. It is therefore of interest and, as will be demonstrated shortly, of fundamental importance to investigate the wind flow relative to the moving pressure field.

Fig. 9 shows the quantity U - c as a function of latitude and pressure-height. U here is the geostrophic zonal wind speed (west wind positive) and c is the west to east speed of the trough or low center at the particular latitude or pressure level. Values of both U and c are 48-hour averages from 15Z March 11 to 15Z March 13. The cross

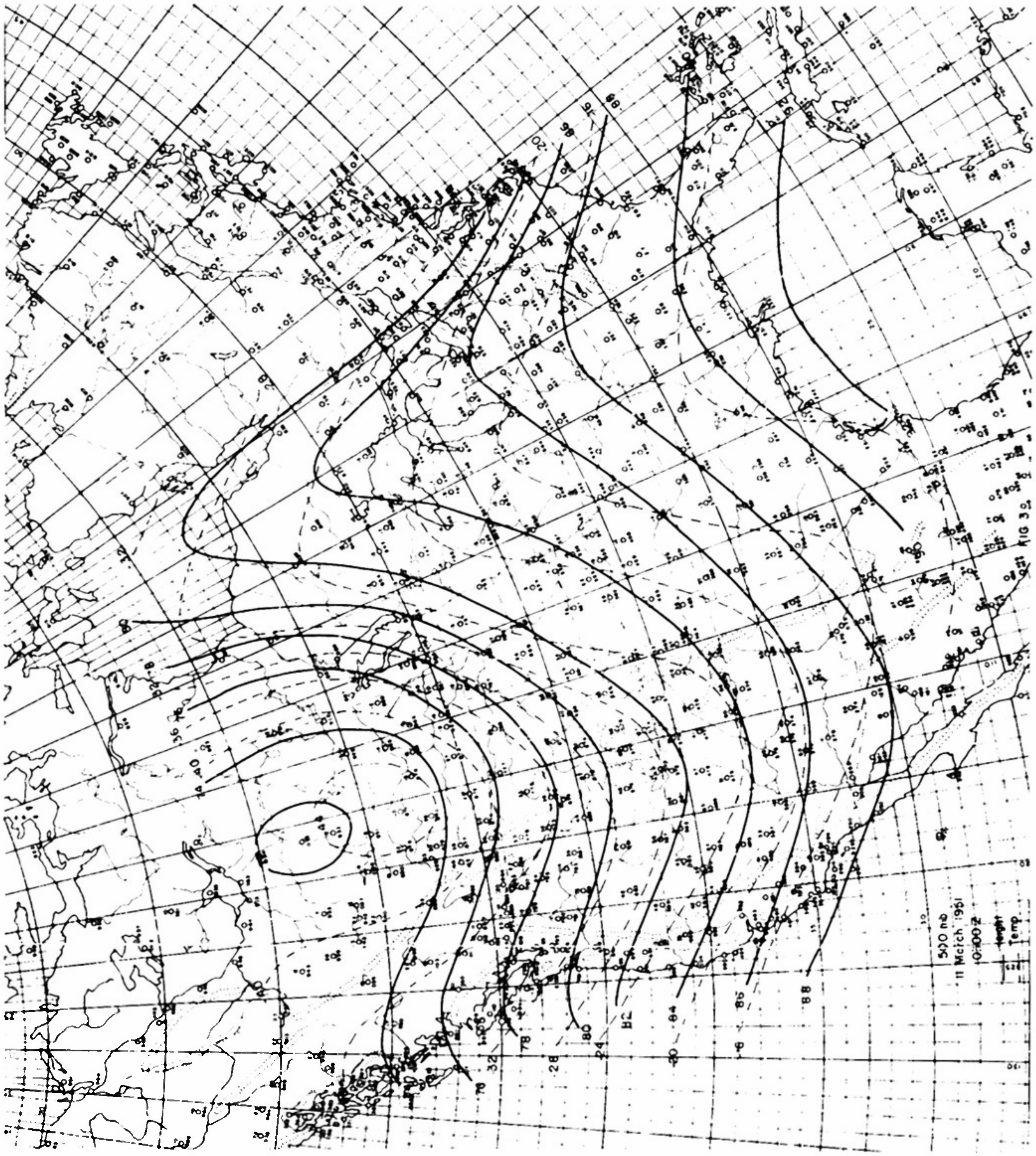


FIG 3

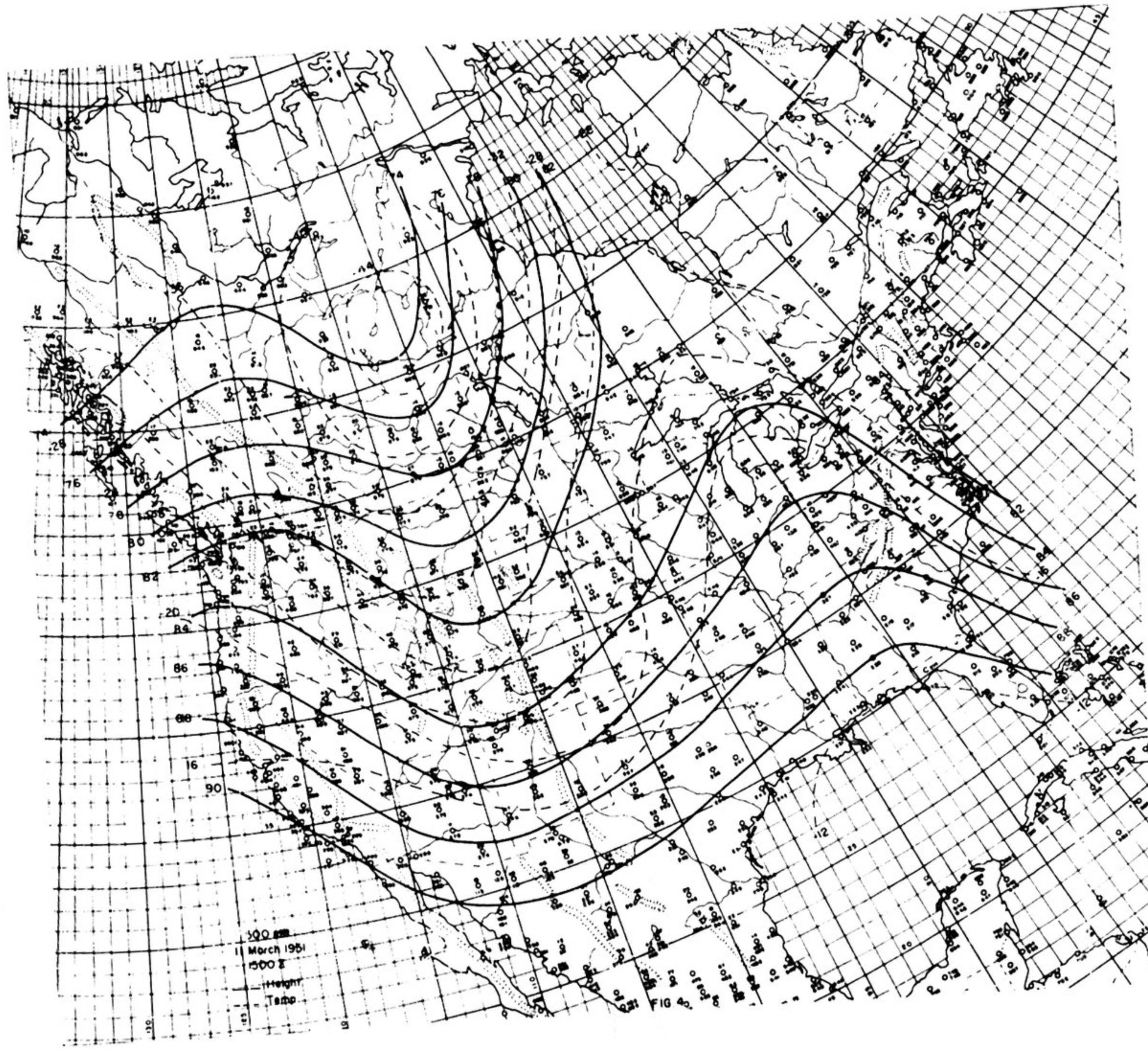


FIG 4a

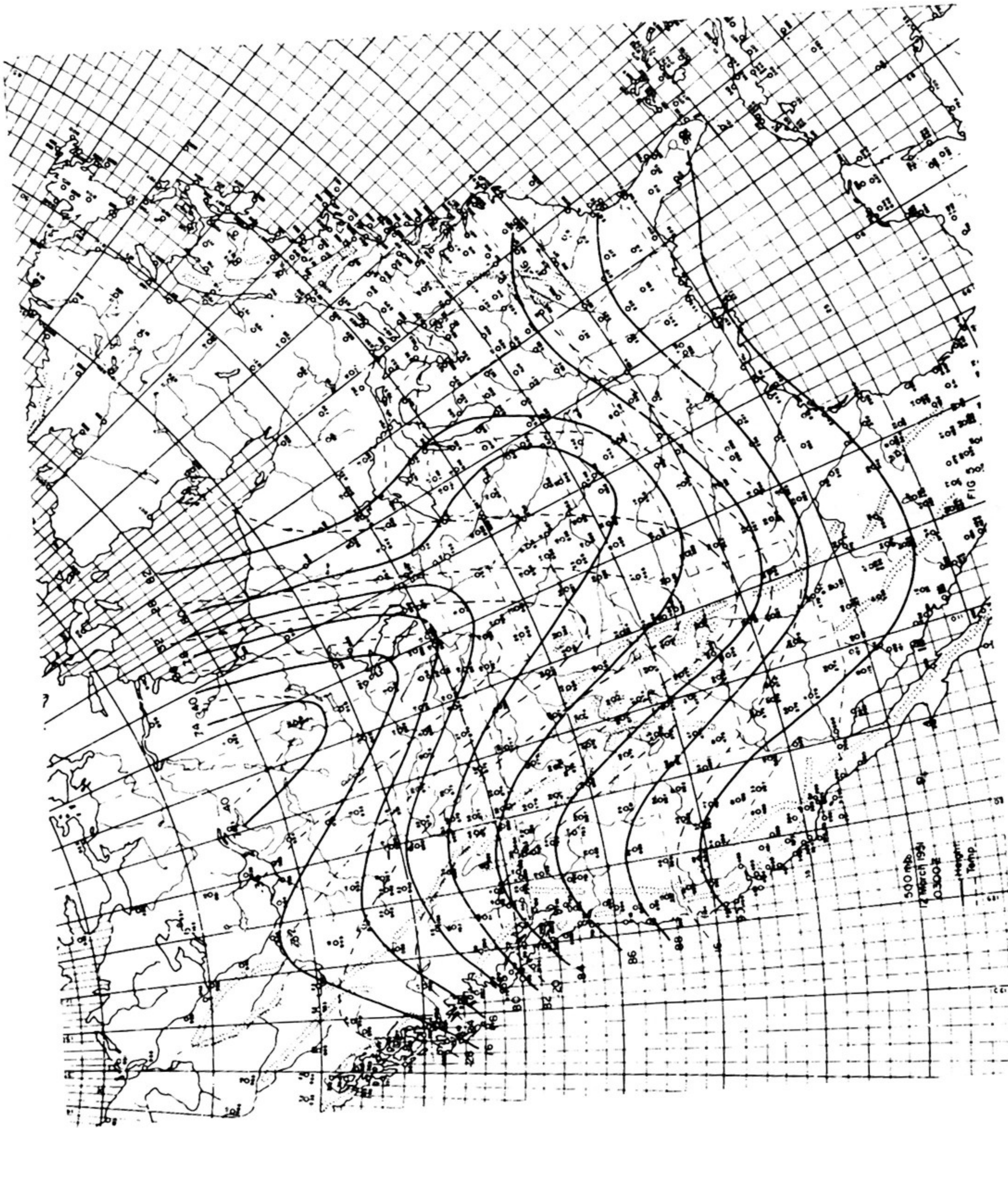


FIG
500 mb
12 March 1951
0300Z
Height
Temp

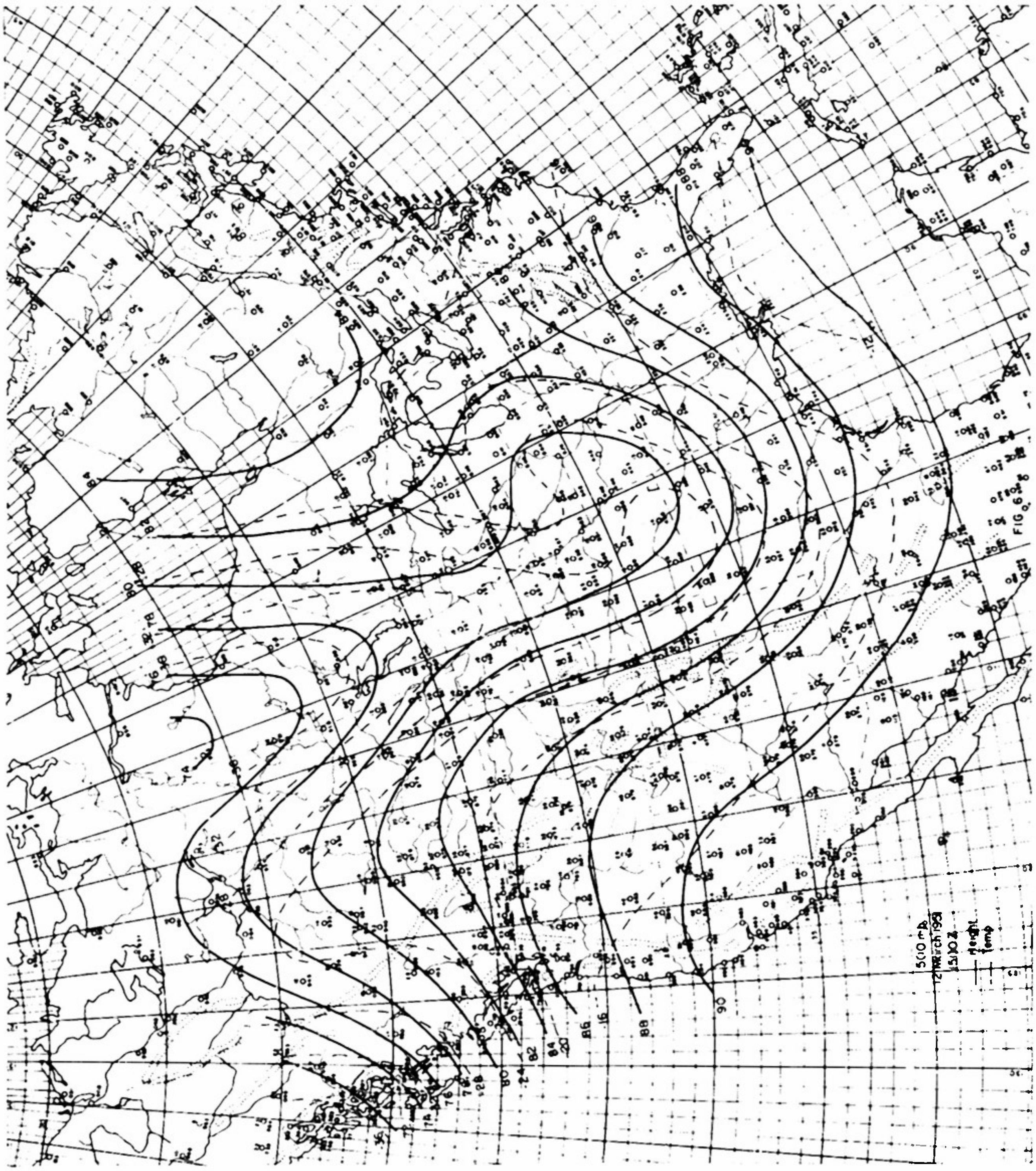
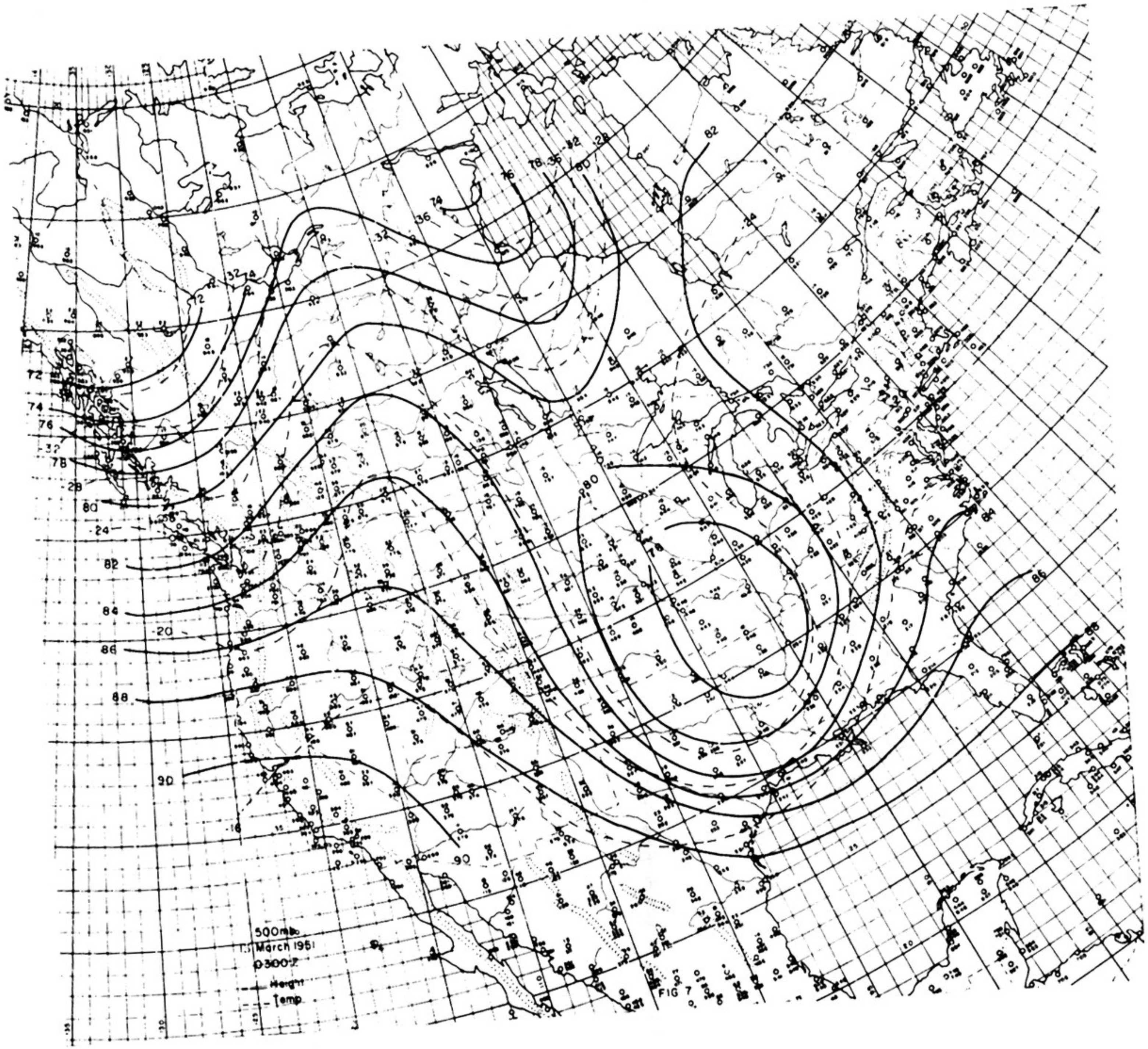


FIG 6
500 mb
Height
Temp


500mb
March 1951
0300Z
Height
Temp
FIG 7

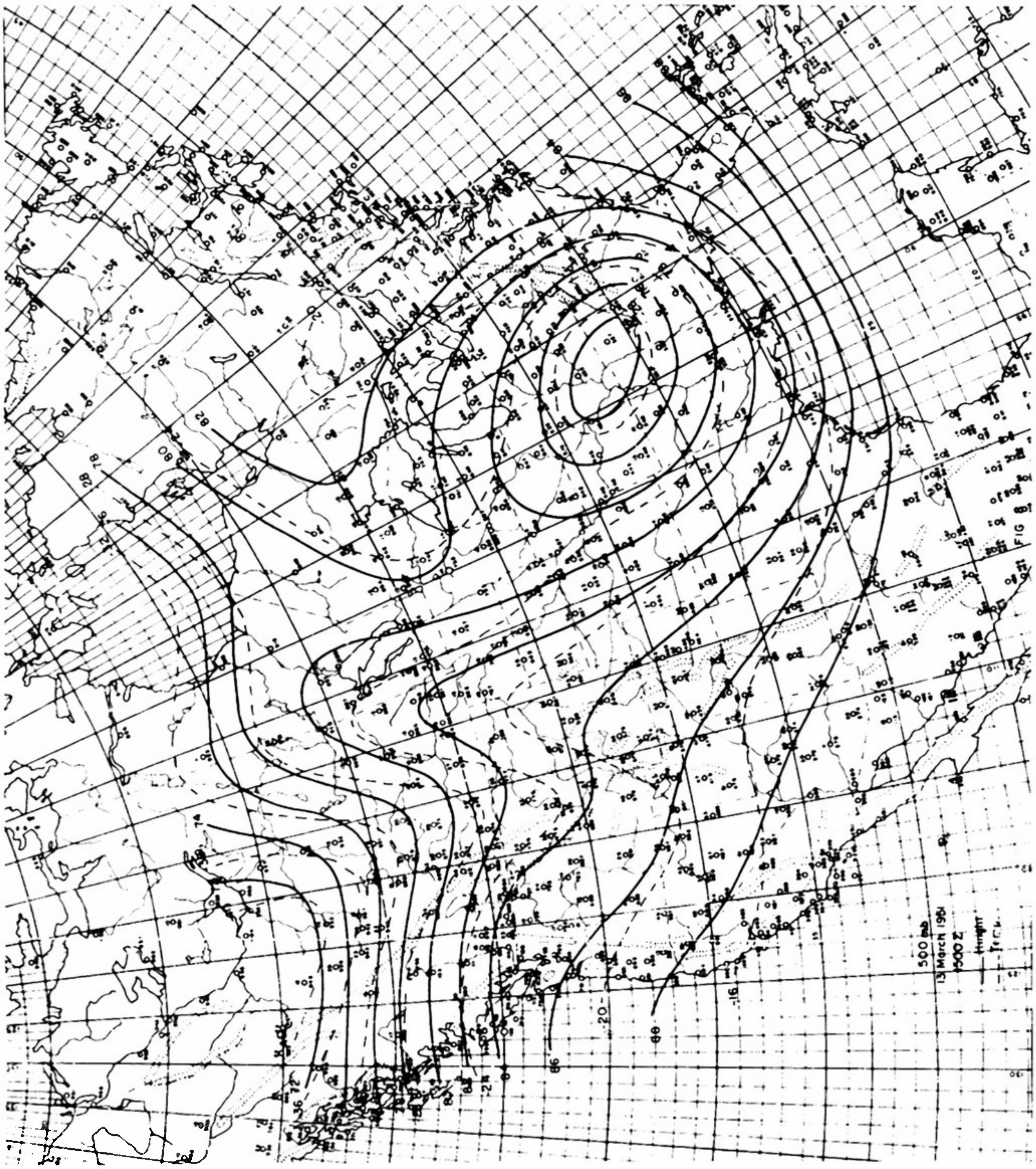


FIG 8

in Fig. 9 indicates the latitude of the closed low at 500 mb at the end of the period.

From the figure it is apparent that in a coordinate system moving with the low air is observed to enter the lower portion of the storm from the forward or eastern edge and the upper portion from the rear or western border. North of the center the inflow from the east extends to higher levels. South of the center it is more shallow and less extensive. These results imply the following conclusions:

1. The air which comprises the final, cold vortex is of vastly different origin at different levels. Therefore it is incorrect to depict the development as occurring symmetrically about the axis.
2. The air at low levels spirals into the vortex from the south and east.
3. The air at high levels enters from the north and west.
4. At intermediate levels the inflow is from the south and east in the northern half, from the north and west in the southern half of the vortex.

b. Vertical Displacements. Next the vertical motions accompanying the cold low formation will be considered. These are important in two ways. They modify the temperature field by adiabatic warming and cooling. Through the equation of continuity they determine the fields of divergence and convergence which in turn determine individual changes in vorticity. It is apparent that a proper scheme of vertical velocities is essential to a consistent thermal and dynamic picture of the cold low.